Integrating Socio-Technical Research with Future Visions for Tidal Energy

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Abstract—An engineering design can be made more sustainable by holistically considering the social, environmental, and economic dimensions of the system. This paper describes the integration of Socio-Technical Integration Research (STIR) into a future visioning exercise for tidal energy systems, both part of a broader Sustainability of Tidal Energy (STE) project. Tidal energy systems convert the energy in fast-moving tidal currents to electricity using multiple tidal turbines. Design convergence has not yet been reached for tidal turbines, so social and environmental considerations have the opportunity to influence design. STIR focuses on reflection during engineering decision making as a way to integrate broader public values in specific research questions. It employs a structured framework for conversation, but the method is also flexible. What sets this STIR study apart from previous STIR research is that the STIRer was not a typical embedded humanist, but rather a trained engineer and a graduate student on the STE research team. Thus the STIR study was conducted between two engineers, who are the Principle Investigator of and the graduate student working on the future visioning project. Both the STIR and future visioning research activities began at the same time and were initially compartmentalized into two separate lines of research within the larger project. During the STIR decision protocol, the student asked the professor about any decisions he was making – these decisions are broad in scope, highly technical, and influenced by many other people's decision making. More than halfway through the study, and after some frustrations with the process, the pair decided to exclusively focus their STIR discussions on their collaborative future visioning research. Once STIR and future visioning were combined, both areas of research improved as a result. The STIR conversations became less rigid, more natural, and more applicable to a characteristic STIR outcome of expanding values. Not only did the STIR study improve, but the future visioning research broadened in scope. STIR allowed the conversation to slow down, deepen, and evolve over time. Expanding considerations was beneficial for content and perspective, expanding alternatives opened up options rather than narrowing down to one design, and the research plan became more inclusive of diverse stakeholder perspectives. The initial compartmentalization of STIR and future visioning was a setback for both studies, and only by integrating them could their full potential be realized.

***Keywords*— STIR = Socio-Technical Integration Research; STE = Sustainability of Tidal Energy; future visioning**

I. Introduction

The "Sustainability of Tidal Energy" (STE) research project takes an interdisciplinary perspective on tidal renewable energy research. Under the STE, faculty and graduate students from Mechanical Engineering, Oceanography, Fisheries Science, and Marine Affairs are all involved in various aspects of tidal energy research. The STE project objectives are to establish a more sustainable pathway for tidal current energy – the conversion of fast moving tidal currents into electricity. Individual tidal turbines are nearing commercial readiness, but the technology has not yet undergone a design convergence. There are still many options under consideration, particularly in terms of how devices are configured into an array of multiple turbines. At its inception, the STE project envisioned the development of a set of tools that could be used to evaluate the sustainability of a scenario for tidal energy development and apply engineering options to refine unsustainable scenarios. While many of the tools were developed as planned, they did not allow for a quantitative evaluation and the scenario aspect of the project evolved to holistically consider sustainable "future visions." Among the STE project's other objectives were identifying opportunities to enhance interdisciplinary research through STIR: Socio-Technical Integration Research. STIR integrates social values into technical research decisions and was selected as a way to enhance the social-technical integration envisioned for the larger project. STIR has been shown to increase reflection and shape research direction [1-7]. STIR combined with future visioning research enabled progress on dealing with uncertainty, taking a broad view, and expanding possible outcomes. Thus, the scenario aspect of the project evolved to holistically consider sustainable future visions. The increasing interaction and integration of STIR with the future visions research are explored in this paper.

A. Sustainability of Tidal Energy Project: Future Visioning

The STE project aims to address basic knowledge gaps around aspects of tidal energy that have inhibited the development of sustainable, large-scale generation operations. For example, a proposed pilot-scale tidal energy project in Puget Sound, WA encountered a number of unexpected stakeholder concerns raised over the course of its permitting process (e.g. tribal fishing rights). This experience is consistent with human dimensions research showing that marine renewable energy projects can fail because of lack of consideration of this social dimension [8].

The initial plan for scenario analysis in the STE project was to have each discipline contribute "toolboxes" (social, environmental, and technical) that could produce a set of metrics to rate the sustainability of a tidal turbine array and guide more sustainable outcomes. Given the degree of uncertainty, a comprehensive set of metrics could not be meaningfully established. However, the overall concept was adapted to consider "future visions" for tidal energy arrays. The future visioning research seeks to identify sustainable designs based on knowledge uncovered through the STE project, lessons learned from global tidal energy development, and expert opinion. Through this, social and environmental dimensions can be linked with engineering design outcomes.

The future visioning research has led to several outcomes. The first is a framework of holistic considerations leading to design philosophies for components of tidal energy arrays [9]. The second is a concept for one future vision that adheres to elements of this philosophy. Going forward, additional future visions will be developed and refined through a stakeholder workshop that brings together many diverse perspectives [9].

B. Sustainability of Tidal Energy Project: STIR

Socio-Technical Integration Research (STIR) is a collaborative method for enhancing the integration of societal goals and values into technical decisions. Developed and piloted in a nanoscale engineering research laboratory [1], the approach was originally developed to assess the possibility and utility of integrating societal concerns directly into nanoscale research and development as mandated by US federal law [10]. STIR has since been deployed in science and engineering laboratories around the world and has been identified as a promising model by the National Science Foundation [11] and Presidential Commission for the Study of Bioethical Issues [12].

STIR studies have been conducted in collaboration with over three-dozen science and engineering research and development laboratories in North America, Europe and Asia. An initial pilot study placed an "embedded humanist," or STIRer, into an engineering research laboratory for 12 weeks in order to "identify and assess opportunities for influencing research decisions in accordance with societal concerns" [1]. The study found that "engineering research decisions were…subject to societal influences" and that engineering researchers became "aware of the possibility of modulating their decisions accordingly." Increased awareness also led one engineering researcher to "alter several decisions as a result of the study" [2]. Following this, 30 coordinated studies that were modeled on the pilot study were conducted with laboratories working on nanotechnology, synthetic biology and other emerging technologies. Like the pilot, these studies found evidence for both the possibility and utility of collaboratively enhancing integration [3-7]. Since then, individual studies associated with the STIR Cities project have begun testing the STIR approach in new contexts, including exploring the effectiveness of technical experts using the method to collaborate amongst themselves on enhancing integration, without an embedded humanist, which is the focus of the present study.

For this study the STIRer and STIRee have a different dynamic than is typical of STIR. Both researchers have the same disciplinary background in mechanical engineering and were working on the future visioning research project together. The STIRer is a first year Masters student at the School of Marine and Environmental Affairs joining the Sustainability of Tidal Energy (STE) research project. The STIRee is an Associate Professor in the Mechanical Engineering department and the Project Investigator of the STE project. In addition to the STIR research study, the STIRee advises the STIRer on the future visioning research project. The STIR study began at the same time as the future visioning research, when the STIRer was entering into the Marine Affairs program and starting research as part of the STE team. For this STIR study, collaborating researchers implemented STIR themselves, rather than embedding a humanist in the lab. Thus, they were embarking on "team based collaborative reflection". Additionally, the research team was starting from an informed perspective because the team was already explicitly considering how human dimensions could influence tidal energy design.

II. STIR Methodology

Socio-technical integration is "any process by which technical experts take into account the societal dimensions of their work as an integral part of this work" [13]. Integration occurs as a normal part of research and design decision making, but is rarely taken as an explicit object of reflection. STIR is intended to enhance awareness of socio-technical integration in real-time, in order to support and enhance it. It uses a decision protocol to structure collaborative interactions and analyzes results using midstream modulation.

A. Midstream Modulation

As stated, technical experts routinely perform socio-technical integration, but usually only in a tacit manner. As they become more aware of the societal dimensions of their work, for instance when they encounter a problematic situation, they can perform integration more deliberately or in a more goal-directed manner. This process of learning and adjustment is described by midstream modulation, which is theorized to occur in three analytically distinct phases that build iteratively on one another:

- *De facto* modulation: Research projects are influenced by internal (cognitive, emotional, ethical) and external (social, economic, material) societal factors.
- *Reflexive* modulation: Researchers experience a heightened awareness of these societal factors interacting and operating in their own decisions.
- *Deliberate* modulation: Researchers change their practices after reflecting on how these societal factors do and could factor into their decisions.

In practice, these three analytically distinct modulation phases iterate and overlap. Theoretically, reflexive modulation only involves a change in awareness, while deliberate modulation involves an actual adjustment in decision-making. In practice, changes in awareness and decision-making can occur simultaneously or at different points in time. Reflexive modulation is a necessary but not sufficient condition for deliberate modulation. The conditions that enable deliberate modulation can be generalized only to a certain extent and must be identified through context-sensitive observation.

It is important to note that reflexive and deliberate modulation can take two forms: first-order and second-order. First-order or goal-directed modulation involves researchers addressing pre-determined goals and objectives, and may involve increases in efficiency or productivity. Second-order or deliberative modulation involves reflecting on goals and objectives, and may involve rethinking broader societal goals or values [7].

B. *Decision Protocol*

The decision protocol is the primary method used in STIR. This consists of four basic questions that may help map the opportunities, considerations, alternatives, and outcomes of routine research decisions [1]. A decision protocol is shown below in figure 1. Typically, the embedded humanist will probe the researcher with questions and fill out this decision protocol from the responses. The protocol is populated based on the collective discussion, largely focused on the STIRee's research.

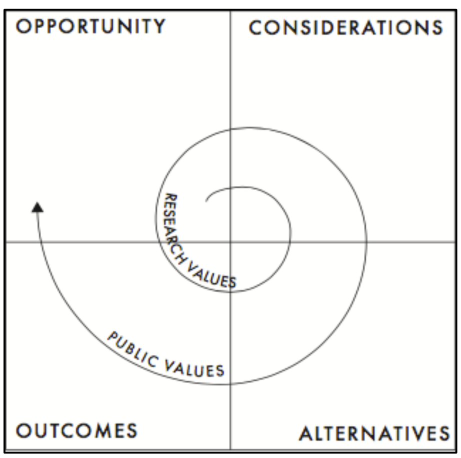

Figure 1. Decision Protocol with arrow indicating conversation flow [14]

While there is structure to the protocol, it is also very open ended. The discussion is free to go in any direction in terms of topic, order of when the quadrants are discussed, and has the ability to circle back around and gain wider perspective on the question [1]. This is depicted in the figure by the spiral arrow, which moves through the quadrants in terms of research values, and then expands to public values. Additionally, since it occurs over 12 weeks, the same decision may be discussed multiple times to capture how the decision making process evolves. The protocol is based on a model of technical decisions that includes four components:

- Occasion: the event or stimulus that sets a decision in motion.
- Considerations: the criteria that determine the response to the occasion.
- Alternatives: the available options for responding to the occasion.
- Outcomes: the actual or anticipated results of selecting one or more alternatives in light of one or more considerations.

The midstream modulation process of moving from awareness to adjustment occurs as a natural part of research. Thus, STIR is used to describe, enhance or, in rare cases, stimulate midstream modulation. Enhancing midstream modulation can take the form of speeding it up, slowing it down, making it more frequent, deepening it, etc. The primary technique for enhancing midstream modulation is through collaboratively mapping out decision components on a regular basis and in real-time by using the decision protocol.

C. *Reflexive Awareness*

The immediate goal of the decision protocol is to stimulate or enhance reflexive learning. Reflexive learning occurs when researchers become more aware of the modulators that influence a decision [1]. Modulators include social norms, values, expectations, and assumptions [1]. Reflexive learning can then lead to changes in behavior through value deliberation and practical adjustment [15]. Value deliberation includes value clarifications, expansions, and considerations. Practical adjustments are changes in practice, and can be material, behavioral, and strategic. The ultimate goal of STIR is to bring technology development into closer alignment with public values, which requires a researcher to consciously adjust their decisions based on these values. Ideally, consideration of social implications will take place in combination with engineering research, and research decisions will be positively affected.

D. *Hypothesis*

The goal of the research is to determine whether, and if so to what extent, STIR yields reflexive learning and goal-directed modulation in this team-based, engineering-led application of the decision protocol. The overall value gained from analysis of decision protocol sessions will explain how this is achieved. In this study in particular, the STIRer and STIRee already have an informed perspective on social dimensions of their research and are collaborators on a research team. The goals are to understand reflexive awareness and practical adjustments as a result of this study. A secondary goal is to explore team based collaborative reflection by an engineering team in order to understand how to institutionalize STIR for research teams. Although a unique study, this matches with the original goals and still contains all the essential elements of a STIR study. It is hypothesized that STIR can be integrated by an engineering team during research projects for ongoing use to increase social reflection into engineering research.

E. *Scope*

STIR was used in a similar way to the pilot study [1]. The STIRer and STIRee research pair thought through the decision protocol together, and let any social values emerge on their own through broad considerations. However, the STIRer (graduate student) did not aim to shape research in a specific way. Initially, the STIRer probed the STIRee (advisor) with questions relating to a wide variety of the STIRee's numerous research decisions, which led the team to spend more time on background explanation than on collaborative mapping and reflection. This led to some frustration for both team members, and eventually led to an epiphany to focus the STIR decision protocols on the research they were already doing together. This resulted in integrating STIR more fluidly with the research process, namely, the future visioning component of the STE project.

F. Study Structure

The STIR process occurred over six months, in combination with the evolution of the future vision research. This study created a process of Team Based Collaborative Reflection which was pursued for this STIR study since the pair of researchers were acting collaboratively, rather than utilizing the model of an embedded humanist with a technical research group. Thus, the study required not only persistence, as seen in other studies [1,4,7], but also a shift in the mode in which the method was used for it to ultimately be beneficial.

The STIR study took place over six months (July 1-December 17, 2015) with 12 non-consecutive weeks of active decision protocols and identical pre- and post-program interviews to gauge the cumulative changes. In past studies, decision protocols were typically spaced at weekly intervals, but this study required the flexibility to have longer times between protocols due to the faculty member's varied research and service requirements. Dr. Brian Polagye (BP) is the STIRee and Ms. Kaylie McTiernan (KM) is STIRer.

G. Analysis

STIR studies measure change in two ways: (1) by comparing identical pre- and post-program interviews used to gauge cumulative changes in discourse; and (2) by documenting fine-grained modulations in a research project over time and correlating these to the collaborative interactions. Correlation is inferred by qualitatively analyzing field notes (which are recorded during and in-between protocol exercises using participant-observation), audio recordings and transcripts, reports from the research participants, and accounts by third parties. Where possible, graphical representation of the research project's decision sequence and triangulation among different sources (STIR investigator, STIR participant, and a third party) are used. Results are presented in the form of narrative reasoning and are typically vetted by the research participants.

Three types of modulation are typical: reflexive learning, or enhanced awareness of societal factors that influence or potentially influence the research process; value deliberation, which can refer to new societal values or a reordering of societal values; and practical adjustments, which refer to changes in material practice, behavior, research direction or strategy. Additionally, in this study it was found that the positive language of STIR reshaped "issues" as "opportunities" while problems became "alternatives." This reframing had an impact on perspective, contributing to the positive influence on future visioning research.

III. RESULTS

A. STIR Modes: from Elicitation to Collaboration

Initially, the future vision research was compartmentalized from STIR. The future vision research furthered the core objectives of STE project (inclusion of social, environmental, and technical drivers for tidal energy array design), while the STIR decision protocol was less tangible in its aim to integrate social considerations in engineering research. Early protocol discussions focused on the most pressing decision relating to any of the STIRee's research projects. It was thought that this would keep the conversation natural, and allow the STIRee to discuss his pending decisions. However, this was not productive for a few reasons. First, because the STIRee has a relatively large and diverse research group (eight graduate students and a research engineer), he makes many disparate decisions – some technical some administrative – on a daily basis. Because the STIRer did not have the same depth and breadth of knowledge as the STIRee, this led to stilted conversations in which the STIRee (BP) spent considerable time providing context for the STIRer (KM) to understand a particular decision. As an example, one protocol discussion (Decision Protocol no. 7 of 12) focused on the specific choice of oceanographic sensors included in an integrated environmental monitoring package – one of which was proving to be unreliable:

> BP "…so basically, [we have to] give up the stereo imaging."
> KM "And what would be the issues with having only a single camera?" *[Here, KM is attempting to identify considerations, but also does not know enough about the topic to help guide the conversation]*
> BP "We can't do stereo [imaging], but that's not necessarily essential for this part of the project."
> KM "And… what do you mean by you can't do stereo imaging?"
> BP "Oh, do you know why we have two cameras on the AMP?" *[The discussion then turns to a short tutorial on stereo imaging]*

The STIRee (BP) felt that he had to fill in the STIRer's knowledge gaps before he could enter into the decision protocol thought process of expanding considerations. Even when STIR has typically been done with researchers at comparable stages of professional development, which is often the case, knowledge and power asymmetries have been a factor in the interactions. In this case, the complications stemming from the asymmetry between a graduate student STIRer and faculty STIRee on the same project team were explicitly acknowledged, which facilitated a shift in the mode by which the method was deployed.

Because of the diversity of topics discussed during the first half of the protocol, it became increasingly difficult to see a coherent narrative binding the discussions. (As we discuss below, this connects with the question of whether STIR can function only as an addition to or as an integral part of engineering research.) The STIRer devoted considerable time contemplating the best topics to discuss during the STIR conversations, while the STIRee became progressively less interested in the wandering nature of the STIR sessions. For the

STIRer, this meant being less in the moment as she focused on trying to get ahead of the conversation with follow up questions. For the STIRee it was clear that he was less interested because he was yawning often (although unintentionally), his tone was serious, and the pace of conversation was ponderous. This is greatly contrasted with the upbeat, fast paced, laughter filled conversations that occurred during the future vision framework and scenario development. Although the pair were both cognizant of these frustrations, neither was comfortable "breaking protocol" from their interpretation of STIR. A meeting on September 4th (between Decision Protocol no. 7 and 8) became a turning point, in which we both realized that they could transform their use of the tool to make it better suit their specific circumstances. This resulted in decision protocols exclusively focusing on future visions as opposed to trying to map all of the STIRee's research decisions (Decision Protocols no. 8-12). There was instantly a better dynamic when they focused on the future visioning research. The STIRer (KM) was able to take a collaborative role in populating the protocol and the conversation became more candid and in the moment.

Once the protocol was focused on future visioning, the dynamic and utility of the conversations changed. The transformation can be seen, for instance, in the evolution of a conversation about turbine rotor types. There are many tidal turbine rotor types, with the most common being similar to horizontal axis wind turbine blades. The first time the STIRer asked about rotor types (Decision Protocol no. 2), the STIRee was reluctant to engage the issue:

> KM: "What about the big question of what type of rotor to go forward with? Do you use a horizontal axis? Do you use a cross flow? I think you wrote, on the spreadsheet [*early framework brainstorming*] somewhere, the kite type, which I'm less familiar with. But would you want to talk about maybe decisions of the...essentially what are the best types? Or is that too broad of a question?"
> BP: "It might be too broad. That's a little hard to...I haven't been thinking much about that question. I have been thinking a lot about what the...kind of the foundation to use, and I've been rolling around different kind of pros, cons in my head."

The STIRer had a hard time broaching the topic and the STIRee had a hard time answering. The response that the STIRee hadn't been "thinking much about that question" is a result of being hesitant to discuss something he was not yet decided on, but in fact it was an area that he had thought a great deal about. The next time the STIRer asked about rotor types was during Decision Protocol no. 4, still prior to integrating the protocol with the future vision research:

> KM: "Another option, you mentioned that you haven't put a lot of thought into it, but maybe just a quick run through of the types of turbine technology - like whether it's axial or cross flow. Maybe just your thoughts on the different alternatives."
> BP: "Okay. In terms of the difference between the technologies…?"
> KM: "Yeah, the differences between tidal technology and what do you think are basically the pros and cons of different ones, and where it's kind of heading in your opinion. And it doesn't have to be well thought out. It could be a quick one."
> BP: "Okay. Well I don't really know where it's heading, is the first thing to say. I guess the starting point for that is that wind energy converged to a three-bladed horizontal axis turbine… more specifically a three-bladed horizontal axis turbine with pitch controls…"
> …
> KM: "Okay. So do you have any sense of what you think might be the best technology? It seems like maybe axial and cross flow. Or do you have a preference in your mind?"
> BP: "I don't really. I like certain aspects of the cross flow technology. And it's a much less explored space, so from a research perspective I think it's very interesting. From a commercial perspective right now, the horizontal axis turbine is a better known technology, and probably a better bet commercially right now."
> KM: "Okay. Then it sounds like possibly you're leaning towards horizontal axis with the open mind to other types of technologies?"
> BP: "No. I wouldn't even say that. I'd say it's really an open question which is best…"
> …
> KM: "I know it's a difficult question, but it's just talking through the options. That gives me a lot of really good information. It doesn't have to be an exact answer."
> BP: "Yeah. I think part of the problem might be this is something I have actually spent a lot of time thinking about, and I may be down too far in the weeds to give you a clear [*single*] answer on it."

The STIRer and STIRee were able to discuss rotor types, but it was still difficult to deal with uncertainty in the topic. Further, the conversation mainly revolved around the two leading types of technologies – axial and cross flow – and their technical characteristics. After adjusting the protocols to focus on the future visions, this conversation took place in a discussion focused on rotor options during Decision Protocol no. 9:

> KM: "So let's discuss types of rotors."
> BP: "[The opportunity should be] which rotor is best."
> KM: "Considerations for what is best..."
> BP: "Best depends on… how do you define it."
> KM: "It could be efficiency…"
> BP: "Let's throw all the components in there – from an economic standpoint it's the levelized cost of energy."
> …
> BP: And then I guess societally the best rotor would be the one that interferes least with existing uses of a location or enables new uses
> KM: "And minimal impact on seascape."
> …
> KM: 'Ya, ya I think it's ok to have those cross topics and break them down."
> BP: "And well, and most of them are cross topics." [That is, they do *not fitting cleanly into a single environmental, societal, technical, or economic "box"]*
> …

BP: "Ok, should we go through alternatives? Fundamentally there are 3 types of rotors: [axial, cross flow, oscillating hydrofoil… and a couple of others that are completely novel]."

STIR became a more tangible asset when we focused on future visioning because we used it as a tool to expand options for possible futures. Additionally, the STIRer (KM) was able to be more in the moment and contribute more to the conversation. The final conversation is clearly much more natural and creative, with both the nominal STIRee and STIRer jointly populating the protocol. There was no longer the sense of needing to narrowly commit to one outcome, and the future visions were an ideal topic to expand considerations and alternatives. It should be noted that the STIR framework is meant to expand considerations and options, and the future visioning research gave further license to be creative and leave options open.

As shown through this progression of dialogue, the traditional STIR approach of returning to the same topic as the decision process unfolded over time was beneficial. STIR encourages digging deep into issues, revealing areas that lacked clarity, and revisiting things over time. It served as a reflection tool that enabled insight to speed up discovery methodically.

The frustrations with the initial rounds of STIR stemmed from moving from topic to topic without a clear objective. Prior to integrating future visioning and STIR, the study was flirting with disaster, to the point that the likely outcome appeared to be an acknowledgement that the only thing learned was that the protocol did not work in this context. However, once the mode of using STIR shifted and it was combined with future visioning, not only did the decision protocols improve, but the future visioning research also significantly improved.

B. Evolution of Future Visioning Research

While STIR and the future visions were initially compartmentalized, in retrospect one can see the indirect effects STIR was having on the future visioning. The main impact was through the adoption of positive language. For instance, "considerations" replaced "issues", when contemplating the economic, environmental, social and technical dimensions of a design option. The future visioning began by compiling a matrix of social, environmental, economic, and social considerations for specific topics (e.g., choice of turbine rotor) with pros and cons enumerated. These were considered in the context of a specific future vision for a sustainable array design [9].

Once STIR and future visioning were integrated, STIR became a method to brainstorm for future visioning and expand research considerations and alternatives. For instance, the idea of incorporating more than one future vision was explicitly discussed during Decision Protocol no. 8:

KM: "Ya so the outcome. What's the best thing going forward now?"

BP: "I think it's worth trying a couple of different approaches because I don't know how the dynamics will be different. It's possible that all will be technically sound, but people like or don't like certain aspects of the system."

KM: "And I think that will be good about having a few visions… I think if we come up with five good options"

BP: "Or maybe three…think about how long it takes to talk through five... it may be information burn out."

This juncture also marked a shift from using the framework to explain the merits of a single future to using it as an expression of a holistic design philosophy against which a range of future visions could be considered. Two of the main array components are rotor and foundation types, so we began thinking of three viable rotor types and three viable foundation types. The initial idea was to mix and match these into three future vision scenarios, as an expansion of alternatives from one future vision. Here it is a mentioned during Decision Protocol no. 9:

BP: "Well I think if you were talking about the mix and match of the matching scenarios… – axial, cross, and oscillating can all be the basis for a scenario."

…

KM: "Ok, so for that reason, it is good to have three very different options just for the sake of discussing different trade offs."

Then on November 13th (between Decision Protocols no. 10 and 11) the discussion progressed further to leaving the options open (i.e., allowing any of the rotor options to be matched with any of the foundation options). This was discussed in the context of a decision to convene a stakeholder workshop on future visions that could bring together experts with diverse backgrounds in biology, regulation, engineering, navigation, fishing, and industry. The goal would be to incorporate a wide range of perspectives and debate, in real time, the merits and drawbacks of different options for sustainable tidal energy arrays. This was unanticipated at the initiation of the future vision research and demonstrates the role of STIR in allowing an objective to be more effectively pursued through expanding both considerations and alternatives.

C. Integration of STIR with Future Visioning

Fundamentally, STIR helped to regulate the pace of conversation, allowing us to better assess a path forward. Moving through opportunities, considerations, alternatives, and outcomes in a structured, consistent manner was useful for thinking through options. The process of expanding both alternatives and considerations helped to break the team out of routine patterns of thinking. For instance, sometimes the best insights came from thinking about extreme negative scenarios. This can be seen in discussing the reason to limit the number of mooring cables in the water during Decision Protocol no. 8:

KM: "[…*discussing options for foundation layout in a design*] And you could add other cables along the way, but then thinking in terms of [your earlier conversation] about [the increased risk of] "clothes-lining" a humpback [whale]."

…

BP: "One of the points that was brought up in the meeting yesterday which I thought was really good is the number of lines in the water. Someone looks at it and goes – 'uhh, you're going to "clothes-line" a humpback.'"

KM. “Right, so try to minimize those while… [Stated while *sketching a modified mooring structure with fewer lines.*]”

…

BP. “How does everything get connected I think is the question” [The *opportunity was now re-framed around collision risk: originally, it was ‘how to handle the buoyancy aspect of the compliant mooring’.]*

And it also allowed the team to discuss some of the broader issues in perspective during Decision Protocol no. 9:

BP: “You’ll probably find that like [if you think of it in terms of a character in a game] when they have different attributes of a character, whether it’s intelligence, strength, dexterity… you can imagine it’s something spread out like that for societal, environmental, economic, and technical [attributes of an array]. You can imagine that there’s some designs that go really hard to one direction and fail at the other three.”

KM: “Like a happy medium.”

BP: “But what you really want it to do is excel at all four.”

KM: “Well ya”

BP: “But that’s really hard to do”

KM: “I’m putting that, excel at all four, is kind of a consideration”

Combining STIR with future visioning allowed us to stretch our conversations further and be more creative in the process. It was a license to expand considerations and alternatives rather than narrowing down prematurely to a single answer.

IV. Discussion

Integrating a more flexible mode of STIR with future visioning benefited both areas of research. The probable impact and scope of future visioning research has substantially increased. Further, this has led to ideas for how to institutionalize STIR for teams of interdisciplinary researchers, absent an embedded humanist. STIR influenced the future visioning through expanding the number of design options. STIR created a multidimensional design space, as opposed to establishing one single future vision. STIR also shaped the strategy for a stakeholder workshop to incorporate more diverse perspectives, an extension of expanding considerations.

The principles of STIR were also applied to refining the framework used to evaluate holistic considerations for tidal energy arrays. The framework, originally unwieldly, was revisited repeatedly, with each STIR conversation clarifying the structure as sub-topics were explored (e.g., options for foundation structures). Initially, considerations were determined to be either social, environmental, economic, or technical, but the final approach allows for a continuous spectrum (e.g., socio-environmental through techno-economic). This spectrum of considerations leads to a design philosophy, by which different design options can be considered in an integrated and holistic manner.

These outcomes exhibit STIR-mediated transformation of material, behavioral, and strategic forms of practical adjustment [14]. Material practical adjustment was exhibited through the evolution of holistic design framework.

De facto: A matrix of distinct social, environmental, technical, and economic considerations for different design options.
Reflexive: Realization that this the framework could not address the complex and connected nature of the considerations.
Deliberate: Adopting a spectrum of considerations leading to a design philosophy provided a coherent narrative for underlying STIR discussions of specific design options.

Behavioral practical adjustment allowed the pair of researchers to bring structure to a complex project and realize the interplay between STIR and future visioning research.

De facto: Faculty and student engaging in STIR study because it has been shown to enhance interdisciplinary research outcomes. (“I’ve been told that eating kale is good for me.”)
Reflexive: Faculty and student working well together on collaborative research related to future visions, but both frustrated with compartmentalized STIR discussions about discrete research decisions. (“This raw kale tastes awful.”)
Deliberate: Faculty and student applying STIR decision protocol to develop interdisciplinary framework for future visions of tidal energy. (“No one told me I couldn’t sauté the kale in butter.”)

Examples of strategic practical adjustment include leaving design options open, planning a stakeholder workshop to bring in more diverse perspectives, and the extension of the future vision exercise from a single summer’s research to the student’s primary Master’s degree research.

De facto: There are social, economic, and environmental dimensions of tidal energy systems. Attempts to describe these ranged from overly rigid (i.e., assigning a numerical rating to a design scenario) to unhelpfully diffuse (i.e., general listing of social, economic, and environmental considerations).
Reflexive: Holistic consideration of design options – changing perspective on the potential scope and impact of future visions research.
Deliberate: Leaving design options open, acknowledging there could be multiple future visions, and planning a stakeholder workshop for inclusion of more diverse perspectives.

De facto: Future visioning and STIR both initiated as summer quarter projects. When the future visioning and STIR research began to overlap, STIR gave structure and guidance to the future visions.
Reflexive: The future visions research, as shaped by STIR became more than just a summer project because of the expansion of design options and decision to hold a stakeholder workshop.
Deliberate: The future visioning research as the primary research trajectory for the student and a mechanism to integrate interdisciplinary research outcomes of the Sustainability of Tidal Energy project.

V. CONCLUSIONS

In hindsight, as is often the case, considering the future visions during a STIR decision protocol makes perfect sense. Many of the frustrations encountered were a direct consequence of an unexamined assumption that they should be kept separate from one another, and that the conversations needed to be formal and rigid. With the benefit of a more collaborative mode of STIR, the future visioning has expanded to include more considerations through a stakeholder workshop. Additionally, using STIR for team based collaborative reflection proved to be a more effective method to assess how to institutionalize STIR. We found benefits and drawbacks that may enlighten future team-based and collaborative modes of STIR conducted in research labs by the researchers themselves, rather than embedded humanists. Some of the main benefits of integrating STIR and future visioning include:

- Positive language reframed problems as opportunities, issues as considerations
- Slowing down and deepening details of the conversation to enhance thought process and bring the team's thoughts into alignment
- Circling back to topics over time and reflecting to assess subtle shifts
- Expanding considerations and alternatives to open up options rather than narrowing to one solution
- Opening up creative space to discuss research from new perspectives and think 'outside the box'

Going forward, STIR will continue to influence the direction of future visions for tidal energy. Specifically, we see STIR as a useful tool for the stakeholder workshop where STIR can serve as a breakout group exercise to shift participants into a creative frame of mind, open to alternatives and new ways of thinking. Additionally, STIR will continue to be a tool used to check in as needed, since it was seen as particularly useful for reflecting on research direction. For example, in the planning stages of the stakeholder workshop, a STIR session on its goals may further enlighten details to make it more successful.

The future vision construct has grown to materially demonstrate the benefits of integrated technical, economic, environmental, and societal considerations towards tidal energy. While teams of researchers may accept the general premise of interdisciplinary ventures, achieving a truly integrated approach may be complicated without a unifying, tangible goal. The STIRee reflects that the insights gained through STIR will impact his future approach to interdisciplinary research.

VI. RECOMMENDATIONS

This collaboration of STIR and future visioning served as meta-engineering, a reflection on the technical details of design to more fully integrate holistic considerations into the research. This indicates that STIR can be institutionalized in engineering labs by allowing groups of engineers to successfully implement STIR in their own projects. After a period of training and an open mind to the process, engineers who are working together on a project can use STIR as a useful tool to enhance their decision making. STIR can be flexible enough to suit a team's individualized needs, can function to slow down and deepen their conversation, and strategically circle back to opportunities over time to assess subtle changes.

This experience also demonstrates the effectiveness of integrated and interdisciplinary research strategies. While opportunities for such research can be relatively rare (e.g., NSF has only conducted a single Sustainable Energy Pathway solicitation to date), these outcomes suggest that such collaborations between social science and engineering may be beneficial for enabling resilient, holistic research projects.

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